8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills were the largest source of anthropogenic methane (CH_4) emissions, accounting for 24 percent of total U.S. CH_4 emissions.[1] Smaller amounts of CH_4 are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of nitrous oxide (N_2O) emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas and ambient air pollutant emissions from the Waste chapter is presented in Table 8-1 and Table 8-2.

Figure 8-1: 2003 Waste Chapter Greenhouse Gas Sources

Overall, in 2003, waste activities generated emissions of 183.8 Tg CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions.

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990		1997	1998	1999	2000	2001	2002	2003
CH_4	**197.1**		**179.0**	**171.0**	**167.7**	**165.0**	**160.9**	**162.6**	**167.9**
Landfills	172.2		147.4	138.5	134.0	130.7	126.2	126.8	131.2
Wastewater Treatment	24.8		31.7	32.6	33.6	34.3	34.7	35.8	36.8
N_2O	**13.0**		**14.7**	**15.0**	**15.4**	**15.6**	**15.6**	**15.7**	**15.9**
Human Sewage	13.0		14.7	15.0	15.4	15.6	15.6	15.7	15.9
Total	**210.1**		**193.7**	**186.0**	**183.1**	**180.6**	**176.5**	**178.3**	**183.8**

Note: Totals may not sum due to independent rounding.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990		1997	1998	1999	2000	2001	2002	2003
CH_4	**9,385**		**8,526**	**8,145**	**7,984**	**7,858**	**7,660**	**7,744**	**7,997**
Landfills	8,202		7,017	6,595	6,382	6,223	6,010	6,039	6,246
Wastewater Treatment	1,183		1,509	1,550	1,602	1,635	1,651	1,705	1,751
N_2O	**42**		**47**	**48**	**50**	**50**	**50**	**51**	**51**
Human Sewage	42		47	48	50	50	50	51	51
NO_x	**+**		**3**	**3**	**3**	**2**	**2**	**2**	**2**
CO	**1**		**5**	**5**	**13**	**8**	**8**	**8**	**8**
NMVOCs	**673**		**157**	**161**	**140**	**119**	**122**	**133**	**125**

Note: Totals may not sum due to independent rounding.

8.1. Landfills (IPCC Source Category 6A1)

Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In 2003, landfill CH_4 emissions were approximately 131 Tg CO_2 Eq. (6,246 Gg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,800

[1] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land-Use Change and Forestry chapter.

operational landfills exist in the United States (BioCycle 2004), with the largest landfills receiving most of the waste and generating the majority of the CH_4.

After being placed in a landfill, biogenic waste (such as paper, food scraps, and yard trimmings) is initially digested by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which can break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases, and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. Methane-producing anaerobic bacteria convert these fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent CH_4, by volume.[2] Significant CH_4 production typically begins one or two years after waste disposal in a landfill and may last from 10 to 60 years.

From 1990 to 2003, net CH_4 emissions from landfills decreased by approximately 24 percent (see Table 8-3 and Table 8-4), with small increases occurring in some interim years. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted by landfill operators, which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of municipal solid waste in landfills, which is related to total municipal solid waste landfilled annually; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place; size, climate); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized in landfills instead of being released into the atmosphere. The estimated annual quantity of waste placed in landfills increased from about 209 Tg in 1990 to 279 Tg in 2003, an increase of 33 percent (see Annex 3.14). During this period, the estimated CH_4 recovered and combusted from landfills increased as well. In 1990, for example, approximately 935 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills. In 2003, the estimated quantity of CH_4 recovered and combusted increased to 5,545 Gg.

Over the next several years, the total amount of municipal solid waste generated is expected to increase slightly. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of CH_4 that is recovered and either flared or used for energy purposes is expected to increase, as a result of a 1996 federal regulation that requires large municipal solid waste landfills to collect and combust landfill gas (see 40 CFR Part 60, Subparts Cc 2002), and the Landfill Methane Outreach Program (LMOP), an EPA program that encourages voluntary CH_4 recovery and use at landfills not affected by the regulation.

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	1997	1998	1999	2000	2001	2002	2003
MSW Landfills	197.2	215.9	219.1	222.3	226.5	231.9	238.6	245.0
Industrial Landfills	13.8	15.1	15.3	15.6	15.9	16.2	16.7	17.2
Recovered								
Gas-to-Energy	(14.0)	(34.7)	(42.4)	(48.0)	(51.9)	(57.5)	(59.1)	(61.9)
Flared	(5.6)	(32.6)	(38.2)	(41.0)	(45.2)	(50.5)	(55.3)	(54.6)
Oxidized[a]	(19.1)	(16.4)	(15.4)	(14.9)	(14.5)	(14.0)	(14.1)	(14.6)
Total	**172.2**	**147.4**	**138.5**	**134.0**	**130.7**	**126.2**	**126.8**	**131.2**

Note: Totals may not sum due to independent rounding.
[a] Includes oxidation at both municipal and industrial landfills.

Table 8-4: CH_4 Emissions from Landfills (Gg)

[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is typically composed of non-methane volatile organic compounds (NMVOCs).

Activity	1990	1997	1998	1999	2000	2001	2002	2003
MSW Landfills	9,391	10,279	10,435	10,588	10,785	11,045	11,364	11,669
Industrial Landfills	657	720	730	741	755	773	795	817
Recovered								
Gas-to-Energy	(669)	(1,652)	(2,018)	(2,287)	(2,472)	(2,738)	(2,814)	(2,946)
Flared	(266)	(1,551)	(1,821)	(1,951)	(2,154)	(2,403)	(2,635)	(2,599)
Oxidized[a]	(911)	(780)	(733)	(709)	(691)	(668)	(671)	(694)
Total	**8,202**	**7,017**	**6,595**	**6,382**	**6,223**	**6,010**	**6,039**	**6,246**

Note: Totals may not sum due to independent rounding.
[a] Includes oxidation at municipal and industrial landfills.

Methodology

Methane emissions from landfills were estimated to equal the CH_4 produced from municipal solid waste landfills, minus the CH_4 recovered and combusted, plus the CH_4 produced by industrial landfills, minus the CH_4 oxidized before being released into the atmosphere:

$$CH_{4,\text{Solid Waste}} = [(CH_{4,MSW} - R) + CH_{4,ind}] - Ox$$

Where,

$CH_{4,\text{Solid Waste}}$	= CH_4 emissions from solid waste
$CH_{4,MSW}$	= CH_4 generation from municipal solid waste landfills,
R	= CH_4 recovered and combusted,
$CH_{4,ind}$	= CH_4 generation from industrial landfills, and
Ox	= CH_4 oxidized from MSW and industrial landfills before release to the atmosphere.

The methodology for estimating CH_4 emissions from municipal solid waste landfills is based on the first order decay model described in the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* and in a background paper prepared by Jensen and Papatti (2002). Values for the CH_4 generation potential (L_0) and rate constant (k) were obtained from an analysis of CH_4 recovery rates for a database of 52 landfills and from published studies of other landfills (RTI 2004; EPA 1998; SWANA 1998; Peer, Thorneloe, and Epperson 1993). The rate constant was found to increase with average annual rainfall; consequently, values of k were developed for 3 ranges of rainfall. The annual quantity of waste placed in landfills was apportioned to the 3 ranges of rainfall based on the percent of the U.S. population in each of the 3 ranges, and historical census data were used to account for the shift in population to more arid areas over time. For further information, see Annex 3.14.

National landfill waste generation and disposal data for 1989 through 2003 were obtained from *BioCycle* (2004). Because *BioCycle* does not account for waste generated in U.S. territories, waste generation for the territories was estimated using population data obtained from the U.S. Census Bureau (2004) and national per capita solid waste generation from *BioCycle* (2004). Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the first order decay model for completeness in accounting for methane generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment, a database of landfill gas-to-energy (LFGTE) projects compiled by EPA's Landfill Methane Outreach Program (LMOP), and a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2004). The three databases were carefully compared to identify landfills that were in two or all three of the databases to avoid double-counting reductions. Based on the information provided by the EIA and flare vendor databases, the CH_4 combusted by flares in operation from 1990 to 2003 was estimated. This quantity likely underestimates flaring, because these databases do not have information on all flares in

operation. Additionally, the EIA and LMOP databases provided data on landfill gas flow and energy generation for 358 landfills with LFGTE projects. If a landfill in the EIA database was also in the LMOP and/or the flare vendor database, the emissions avoided were based on the EIA data because landfill owners or operators reported the amount recovered based on measurements of gas flow and concentration, and the reporting accounted for changes over time. If both flare data and LMOP recovery data were available for any of the remaining landfills (i.e., not in the EIA database), then the emissions recovery was based on the LMOP data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare data, on the other hand, only provided a range of landfill gas flow for a given flare size. Given that each LFGTE project was likely to also have had a flare, double counting reductions from flares and LFGTE projects in the LMOP database was avoided by subtracting emissions reductions associated with LFGTE projects for which a flare had not been identified from the emissions reductions associated with flares.[3]

Emissions from industrial landfills were assumed to be equal to seven percent of the total CH_4 emissions from municipal landfills (EPA 1993). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten percent of the CH_4 generated that is not recovered (Mancinelli and McKay 1985; Czepiel et al. 1996). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial landfills.

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is not available for the waste placed in every landfill for each year of its operation—a fundamental factor that affects CH_4 production. The heterogeneity of waste disposed in landfills is uncertain as well. The approach used here assumes that the CH_4 generation potential and the rate of decay that produces CH_4 as determined from several studies of CH_4 recovery at landfills are representative of U.S. landfills and reflects this heterogeneity. Also, the approach used to estimate the contribution of industrial non-hazardous wastes to total CH_4 generation introduces uncertainty. Aside from uncertainty in estimating CH_4 generation potential, uncertainty exists in the estimates of oxidation efficiency.

The N_2O emissions from application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills would be relatively small because the microbial environment in landfills is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. The total nitrogen (N) in sewage sludge increased from 189 to 247 Gg total N between 1990 and 2002. The quantity of sewage sludge applied to landfills decreased from 28 to 11 percent from 1990 to 2001 (EPA 1993).

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH_4 emissions in 2003 were estimated to be between 84.0 and 152.2 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of 36 percent below to 16 percent above the 2003 emission estimate of 131.2 Tg CO_2 Eq.

Table 8-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2003 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)	(%)

[3] Due to the differences in referencing landfills and incomplete data on the national population of flares, matching flare vendor data with the LFGTE data was problematic and a flare could not be identified for each of the LFGTE projects. Because each LFGTE project likely has a flare, the aggregate estimate of emission reductions through flaring was reduced by the LFGTE projects for which a specific flare could not be identified. This approach eliminated the potential for double counting emissions reductions at landfills with both flares and a LFGTE project.

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Landfills	CH_4	131.2	84.0	152.2	-36%	+16%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Recalculations Discussion

The estimates for the current inventory are based on the first order decay model rather than the linear regression model for 30-year waste in place used for previous inventories. The first order decay model was recommended by U.S. landfill and landfill gas experts and is the preferred approach in the IPCC guidance. Data are now available to develop reliable estimates of the two parameters needed for the first order decay model: CH_4 generation potential and the first order decay rate constant. In the past, these parameters were considered highly variable, thus making the first order decay methodology less desirable.

In addition to the change in method, improved estimates of the annual quantity of waste placed in landfills were developed, particularly for the time period of 1960 through 1988. These two methodological improvements resulted in a reduction in the estimate of CH_4 generation of approximately 20 percent for 1990 and 27 percent for 2002. About half of this reduction is due to the use of the first order decay model to estimate emissions, while the other half is due to the improved estimates of the annual quantity of waste placed in landfills.

Another revision was incorporating data from the EIA to improve estimates of emissions avoided by LFGTE projects and flaring. The use of the EIA data resulted in a decrease of about 11 percent in CH_4 emissions avoided (using 2002 as an example), primarily due to improved estimates for landfills with flares. Changes were also made to the LFGTE database used to estimate emissions avoided by these projects. The changes included corrections to megawatt capacity and gas flow rates, adding new projects that started in 2003, and accounting for projects that shut down. These changes had only a very small effect on emissions avoided by LFGTE projects. Overall, these changes resulted in an average annual decrease of 52.9 Tg CO_2 Eq. (26 percent) in CH_4 emissions from landfills for the period 1990 through 2002.

Planned Improvements

For the future inventories, efforts will be made to improve the estimates of CH_4 generation at industrial landfills and estimates of oxidation, especially for landfills with gas recovery systems. Improvements to the flare database will be investigated, and an effort will be made to identify additional landfills that have flares. The parameters for the first order decay model will be re-evaluated as more data become available.

8.2. Wastewater Treatment (IPCC Source Category 6B)

Wastewater from domestic (municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur off-site or on-site. For example, in the United States, approximately 25 percent of domestic wastewater is treated in septic systems or other on-site systems. Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces methane. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions.

The organic content, expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD), determines the methane producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. COD refers to the amount of oxygen consumed under specified conditions in the oxidation of the organic and oxidizable inorganic matter and is a parameter typically used to characterize industrial wastewater.

In 2003, CH_4 emissions from domestic wastewater treatment were estimated to be 19.8 Tg CO_2 Eq. (944 Gg). Emissions have increased since 1990 in response to the increase in the U.S. human population. Also, the per capita organic wastewater loading has increased. Industrial emission sources include wastewater from the pulp and paper, meat and poultry processing, and the vegetables, fruits and juices processing industry.[4] In 2003, CH_4 emissions from industrial wastewater treatment were estimated to be 16.9 Tg CO_2 Eq. (807 Gg). Table 8-6 and Table 8-7 provide emission estimates from domestic and industrial wastewater treatment.

Table 8-6: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990		1997	1998	1999	2000	2001	2002	2003
Domestic	11.4		15.8	16.5	17.1	17.8	18.5	19.2	19.8
Industrial*	13.5		15.9	16.1	16.5	16.5	16.2	16.7	16.9
Total	**24.8**		**31.7**	**32.6**	**33.6**	**34.3**	**34.7**	**35.8**	**36.8**

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industry.
Note: Totals may not sum due to independent rounding.

Table 8-7: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990		1997	1998	1999	2000	2001	2002	2003
Domestic	543		751	783	815	848	880	912	944
Industrial*	640		758	767	787	788	771	794	807
Total	**1,183**		**1,509**	**1,550**	**1,602**	**1,635**	**1,651**	**1,705**	**1,751**

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industry.
Note: Totals may not sum due to independent rounding.

Methodology

Domestic wastewater CH_4 emissions were estimated using the default IPCC methodology. National population data for 1990 to 2003, used in the domestic wastewater emissions estimates, were based on data from the U.S. Census Bureau (2004). For BOD_5 for domestic wastewater, two data points were available for 1991 and 2003 (Metcalf & Eddy 1990; Metcalf & Eddy 2003).[5] The BOD loadings for intervening years were obtained by linear interpolation. The emission factor (0.6 kg CH_4/kg BOD_5) was taken from IPCC *Good Practice Guidance* (IPCC 2000). The percent of wastewater BOD_5 that was anaerobically digested was assumed to be 16.25 percent. This value also accounts for U.S. septic systems and is based on expert judgment and on septic system usage data from EPA (1996).

Table 8-8: U.S. Population (Millions) and Wastewater BOD_5 Produced (Gg)

Year	Population	BOD_5
1990	254	5,566
1997	277	7,706
1998	280	8,032
1999	283	8,363
2000	287	8,695
2001	289	9,021
2002	292	9,351
2003	295	9,685

[4] Industrial wastewater emissions from petroleum systems are included in the petroleum systems section in the Energy chapter. Other industrial sectors include organic chemicals, starch production, alcohol refining, creameries, and textiles, however emissions from these sectors are considered to be insignificant.

[5] BOD_5 is the 5-day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 2003).

Methane emissions estimates from industrial wastewater were developed according to the methodology described in the IPCC (2000). Industry categories that are likely to have significant CH_4 emissions from their wastewater treatment were identified. High volumes of wastewater generated and a high organic COD wastewater load were the main criteria. The top three industries that met these criteria included pulp and paper manufacturing, meat and poultry packing, and vegetables, fruits and juices processing.

Methane emissions from these categories were estimated by multiplying the annual product output (metric tons/year) by the average outflow (m^3/metric ton of output), the organics loading in the outflow (grams of organic BOD/m^3), the emission factor (grams CH_4/grams BOD), and the percentage of organic BOD assumed to degrade anaerobically. In developing estimates for the vegetables, fruits, and juices category, COD was used instead of BOD, because no accurate BOD numbers were available. The emission factor used for pulp and paper as well as meat and poultry wastewater is 0.6 kg CH_4/kg BOD_5, whereas the emission factor for vegetables, fruits and juices category is 0.25 kg CH_4/kg COD (IPCC 2000). The pertinent industry-specific parameters are specified below.

Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999, Nemerow and Dasgupta 1991). The most important step is lagooning for storage, settling, and biological treatment (secondary treatment).

In determining the percent that degraded anaerobically, both primary and secondary treatment were considered. Primary treatment lagoons are aerated to reduce anaerobic activity. However, the lagoons are large and zones of anaerobic activity may occur and, consequently, the primary lagoons are assumed to be 1.4 percent anaerobic. Approximately 42 percent of the BOD passes on to secondary treatment, which is less likely to be aerated (EPA 1993). It was assumed that 25 percent of the BOD in secondary treatment lagoons degrades anaerobically, while 10 percent passes through to be discharged with the effluent (EPA 1997a). Consequently, the overall percentage of wastewater organics that degrade anaerobically was determined to be 10.3 percent (i.e., 58% × 1.4% + 42% × 90% × 25%). A time series of CH_4 emissions for post-1990 years was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). The overall wastewater outflow was estimated to be 85 m^3/metric ton, and the average BOD loading entering the secondary treatment lagoons was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993, WorldBank 1999).

The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps and dissolved air flotation. Production data, in carcass weight for the meat and poultry industry, were obtained from the U.S. Census (2004). EPA (2002) provided wastewater flows into the anaerobic lagoons of 7.9 and 16.6 m^3/metric ton for meat and poultry production, respectively. The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively, while 90 percent of organic BOD is believed to degrade anaerobically in the lagoon (EPA 1997b).

Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to the sewer. This industry is likely to use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Consequently, 5 percent of these wastewater organics are assumed to degrade anaerobically. The USDA National Agricultural Statistics Service (USDA 2004) provided production data for the fruits, vegetables, and juices processing sector. Outflow data for various subsectors (canned fruit, canned vegetables, frozen vegetables, fruit juices, jams, baby food) were obtained from World Bank (1999) and an average wastewater outflow of 5.6 m^3/metric ton was used. For the organics loading, a COD value of 5 g/liter was used (EPA 1997b).

Table 8-9: U.S. Pulp and Paper, Meat and Poultry, and Vegetables, Fruits and Juices Production (Tg)

Year	Pulp and Paper	Meat (carcass weight)	Poultry (carcass weight)	Vegetables, Fruits and Juices
1990	128.9	17.9	10.6	30.2
1991	129.2	18.5	11.2	31.3
1992	134.5	18.7	12.0	33.5
1993	134.1	18.9	12.3	34.1

1994	139.3	19.2	13.2	37.3
1995	140.9	19.8	13.8	36.8
1996	140.3	19.8	14.5	36.4
1997	145.6	19.7	15.0	37.7
1998	144.0	20.5	15.1	36.5
1999	145.1	21.0	16.0	37.4
2000	142.8	21.0	16.4	38.9
2001	134.3	20.8	16.8	35.0
2002	137.5	21.5	17.3	36.7
2003	140.0	21.8	17.6	34.4

Uncertainty

Significant uncertainties are associated with the industrial wastewater emission estimates. Wastewater outflows and organics loadings vary considerably for different plants and different sub-sectors (e.g., paper vs. board, poultry vs. beef, or baby food vs. juices). For pulp and paper industrial wastewater, five key variables were simulated: material output, with a standard deviation of 10 percent; wastewater outflow, with a standard deviation of 48 percent; BOD_5 concentration, with a standard deviation of 25 percent; percent anaerobically treated, with a standard deviation of 50 percent; and the BOD_5 IPCC methane emission factor, with a standard deviation of 30 percent. For industrial wastewater from meat and poultry processing, five key variables were simulated: material output, with a standard deviation of 10 percent; wastewater outflow, with a standard deviation of 59 percent; BOD_5 concentration, with a standard deviation of 51 percent; percent anaerobically treated, with a standard deviation of 10 percent; and the BOD_5 IPCC methane emission factor, with a standard deviation of 30 percent. For industrial wastewater from processing fruit and vegetables, five variables were simulated: material output, with a standard deviation of 10 percent; wastewater outflow, with a standard deviation of 55 percent; COD_5 concentration, with a standard deviation of 60 percent; percent anaerobically treated, with a standard deviation of 50 percent; and the BOD_5 IPCC methane emission factor, with a standard deviation of 30 percent.

In summary, uncertainties for outflows are approximately 50 percent for the different source categories and are based on a standard deviation calculation for meat and poultry, and on expert judgment and the literature for the pulp and paper and the vegetables, fruits, and juices category (Nemerow and Dasgupta 1991; World Bank 1999). Uncertainties for organic loadings are based on the same approach and are estimated at 25, 50, and 60 percent for pulp and paper, meat and poultry, and fruits, vegetables and juices, respectively. The uncertainty associated with the degree in which anaerobic degradation occurs in treatment systems is estimated at 50 percent for the pulp and paper and vegetables, fruits, and juices categories, while this factor for the meat and poultry industry is 10 percent, because the flow data are from the entrance of the anaerobic lagoons.

For domestic wastewater uncertainty, a normal probability distribution was assumed for the four key variables simulated: population, with a standard deviation of 5 percent; BOD_5, with a standard deviation of 30 percent; percent of wastewater treated anaerobically, with a standard deviation of 25 percent; and the BOD_5 IPCC CH_4 emission factor, with a standard deviation of 30 percent.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-10. Wastewater treatment CH_4 emissions in 2003 were estimated to be between 25.2 and 50.3 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of 32 percent below to 37 percent above the 2003 emission estimate of 36.8 Tg CO_2 Eq.

Table 8-10: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (Tg CO_2 Eq. and Percent)

Source	Gas	2003 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound

Wastewater Treatment	CH_4	36.8	25.2	50.3	-32%	+37%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Recalculations Discussion

Population estimates for the United States from 1990 through 2002 have been adjusted to include U.S. territories (i.e., American Samoa, Guam, Northern Mariana Islands, and the Virgin Islands). Emission estimates from previous years have only considered estimates of U.S. states and Puerto Rico. On average, updated U.S. population estimates increased total annual CH_4 emissions from wastewater treatment by less than one percent.

The time series for domestic wastewater has been updated due to an adjustment in the per capita BOD factor. The BOD factor changed from a constant value of 0.06 kg per capita per day to an increasing value from 0.06 in 1990 to 0.09 kg per capita per day in 2003. Compared to 2002 estimates, methane emissions from domestic wastewater increased 37 percent. The time series for industrial wastewater changed because more detailed field data became available for the meat and poultry industry (EPA 2002) that include new flow and organic loading data. As a result, estimates for the meat and poultry industrial subcategories have been separated. Organic matter loading calculations are also now based on BOD rather than COD estimates. The new flow data reflect field measurements at the anaerobic lagoon inlet, as opposed to more general plant outflow data. Industrial CH_4 emissions increased 14 percent compared to 2002 estimates, as a result of the more detailed meat and poultry data and a slight increase in pulp and paper production. The total 2002 CH_4 emissions from wastewater treatment increased by 25 percent compared to the emissions in the previous Inventory. Overall, these changes resulted in an average annual increase of 3.8 Tg CO_2 Eq. (14 percent) in CH_4 emissions from wastewater treatment for the period 1990 through 2002.

Planned Improvements Discussion

The Authors/Experts Meeting for the Preparation of 2006 IPCC National Greenhouse Gas Inventories Guidelines for the Wastewater Sector, held in November 2004, will likely generate improved methodological data. Improvements will be planned accordingly.

8.3. Human Sewage (Domestic Wastewater) (IPCC Source Category 6B)

Domestic human sewage is usually mixed with other household wastewater, which includes shower drains, sink drains, washing machine effluent, etc. and transported by a collection system to either a direct discharge, an on-site or decentralized wastewater treatment system, or a centralized wastewater treatment system. Decentralized wastewater treatment systems are septic systems and package plants. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. Often, centralized wastewater treatment systems also treat certain flows of industrial, commercial, and institutional wastewater. After processing, treated effluent is discharged to a receiving water environment (e.g., river, lake, estuary, etc.), or applied to soils, or disposed of below the surface.

Nitrous oxide may be generated during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate via nitrification, an aerobic process converting ammonia-nitrogen into nitrate (NO_3^-). Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). Nitrous oxide can be an intermediate product of both processes, but is more often associated with denitrification.

The United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from centralized wastewater treatment processes; and emissions from effluent that has been discharged into aquatic environments. The 2003 emissions of N_2O from wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (0.9 Gg) and 15.6 Tg CO_2 Eq. (50 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 15.9 Tg CO_2 Eq. (51 Gg) (see Table 8-11). Emissions from wastewater treatment processes have gradually increased as a result of increasing U.S. population and protein consumption.

Table 8-11: N_2O Emissions from Human Sewage (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	13.0	42
1997	14.7	47
1998	15.0	48
1999	15.4	50
2000	15.6	50
2001	15.6	50
2002	15.7	51
2003	15.9	51

Methodology

The IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) assumes that nitrogen disposal, and thus N_2O emissions associated with land disposal, subsurface disposal, and domestic wastewater treatment are negligible and all nitrogen is discharged directly into aquatic environments. For the United States, N_2O emissions from domestic wastewater (human sewage) were estimated using the IPCC methodology with three modifications:

- In the United States, a certain amount of nitrogen is removed with the sewage sludge, which is land applied, incinerated or landfilled (N_{sludge}). The nitrogen disposal into aquatic environments is reduced to account for the sewage sludge application.

    - The IPCC methodology uses annual, per capita protein consumption (kg/year). This number is likely to underestimate the amount of protein entering the sewer or septic system. Food (waste) that is not consumed is often washed down the drain, as a result of the use of garbage disposals. Also, bath and laundry water can be expected to contribute to nitrogen loadings. A factor of 1.4 is introduced to account for non-consumption nitrogen.[6] Furthermore, a significant quantity of industrial wastewater (nitrogen) is co-discharged with domestic wastewater. To account for this, a factor of 1.25 is introduced.[7] In summary, a factor of 1.75 (1.4 × 1.25) is used to account for the extra nitrogen discharge from kitchen, bath, and laundry wastes, as well as industrial wastewater that is co-discharged into sewers, based on Metcalf & Eddy (1991) and expert judgment.

- Process emissions from wastewater treatment plants are not accounted for in the current IPCC methodology. To estimate N_2O emissions from U.S. wastewater treatment plants, an overall emission factor (4 g N_2O/person.year) was introduced. This emission factor is based on a factor of 3.2 g N_2O/person.year (Czepiel 1995) multiplied by the 1.25 factor mentioned above, which adjusts for co-discharged industrial nitrogen and is based on expert judgment. The nitrogen quantity associated with

[6] Metcalf & Eddy (1991) provides an indication of the nitrogen concentration of 40 mg Total Kjeldahl Nitrogen (TKN)/liter for average wastewater from residences, which includes bathwater, laundry, and the use of garbage disposals. According to the NEEDS Survey (1996), the total volume of wastewater generated in the US in 1996 was 32,175 million gallons per day (MGD), serving 189,710,899 people (72 percent of population, not including the septic system users). In 1996, the per capita TKN loading was: 40 [mg/l] × 32,175 × 10^6 [gal/day] × 3.8 [l/gal] × 365 days/yr × 1/(189.7 × 10^6) × 10^{-6} = 9.4 [kg TKN/yr.person]. Average protein intake in 1996 was 41 kg/year (6.6 kg N/year), leading to a factor of 1.4 (9.4/6.6).

[7] The type, composition, and quantity of this co-discharged wastewater will vary greatly between municipalities. Metcalf & Eddy (1991) provide an indicative nitrogen loading of 20 to 85 mg TKN/liter (average 55) for combined residential and industrial wastewater, while residential wastewater loading was roughly estimated at 40 mg TKN/liter (see footnote 1). Until better data become available, the amount of N in wastewater was increased by 10 mg/l to account for industrial co-discharge (factor of 1.25.)

these emissions (NWWT) is calculated by multiplying the N_2O emitted by (2 × 14)/44 and is subtracted from the total quantity of nitrogen that is ultimately disposed into the aquatic environment.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This methodology is illustrated below:

$$N_2O(s) = (US_{POP} \times 0.75 \times EF_1 \times 10^{-3}) + \{[(Protein \times 1.75 \times Frac_{NPR} \times US_{POP}) - N_{WWT} - N_{sludge}] \times EF_2 \times {}^{44}/_{28}\}$$

where,

$N_2O(s)$ = N_2O emissions from domestic wastewater ("human sewage") [kg/year]
US_{POP} = U.S. population
0.75 = Fraction of population using centralized wastewater treatment plants (as opposed to septic systems)
EF_1 = Emission factor (4 g N_2O/person.year) expressing emissions from the centralized wastewater treatment plants
Protein = Annual per capita protein consumption [kg N/(person.year)]
1.75 = Fraction of non-consumption protein in domestic wastewater
$Frac_{NPR}$ = Fraction of nitrogen in protein (i.e., 0.16 kg N/kg protein)
N_{WWT} = Quantity of wastewater nitrogen removed by wastewater treatment processes [(US_{POP} × 0.75 × EF_1× 10^{-3}) × ${}^{28}/_{44}$] (kg N/year).
N_{sludge} = Quantity of sewage sludge N not entering aquatic environments (kg N/year)
EF_2 = Emission factor (kg N_2O-N/kg sewage-N produced)
(${}^{44}/_{28}$) = Molecular weight ratio of N_2O to N_2.

U.S. population data were taken from the U.S. Census Bureau (2003). The fraction of the U.S. population using wastewater treatment plants is from the NEEDS Survey (EPA 1996). The emission factor (EF_1) to estimate emissions from wastewater treatment is based on Czepiel, et al. (1995). Data on annual per capita protein intake were provided by the United Nations Food and Agriculture Organization for the 1990 to 2002 time frame (FAO 2004). Because data on protein intake were unavailable for 2003, the value of per capita protein consumption was extrapolated from previous years. Table 8-12 presents the data for U.S. population and average protein intake. An emission factor to estimate emissions from effluent (EF_2) has not been specifically estimated for the United States, thus the default IPCC value (0.01 kg N_2O-N/kg sewage-N produced) was applied. The fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Table 8-12: U.S. Population (Millions) and Average Protein Intake [kg/(person.year)]

Year	Population	Protein
1990	254	39.2
1997	277	40.9
1998	280	41.2
1999	283	42.0
2000	287	41.9
2001	289	41.8
2002	292	41.6
2003	295	41.8

Uncertainty

Nitrous oxide emissions from wastewater treatment are estimated to be substantially less than emissions from effluent-surface water. Thus, this wastewater treatment subcategory was not considered in the uncertainty analysis. A triangular distribution was used to simulate land application of sludge as defined for the agricultural soil management sector. The same distribution was assumed for landfilled sludge. The means for the distributions were the estimates used for the 2003 inventory estimate. Based on professional judgment, the standard deviation for population was 5 percent, the standard deviation for per capita protein consumption was 5 percent, the standard deviation of the fraction of nitrogen in protein ($Frac_{NPR}$) was 2 percent, and the standard deviation of the non-consumption protein in domestic wastewater was 25 percent based on professional judgment. The standard

deviation emission factor for effluent is 80 percent based on the range provided in IPCC (1996). For the triangular distributions, the lower bound and upper estimates for the land applied and landfilled sludge were 50 percent below and above the respective estimates used for the 2003 inventory. A normal distribution was used to simulate five variables: population, per capita protein intake data, fraction of nitrogen in protein ($Frac_{NPR}$), non-consumption protein in domestic wastewater, and the IPCC emission factor.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-13. Human sewage N_2O emissions in 2003 were estimated to be between 4.2 and 29.9 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of 74 percent below to 88 percent above the 2003 emission estimate of 15.9 Tg CO_2 Eq.

Table 8-13: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Human Sewage (Tg CO_2 Eq. and Percent)

Source	Gas	2003 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Human Sewage	N_2O	15.9	4.2	29.9	-74%	+88%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

An IPCC Tier 1 level QA/QC verification was performed. During the QA/QC process the values for Wastewater BOD produced per capita (kg/capita/day) were adjusted to be based on a calculated rather than estimated interpolated value between the reported 1990 and 2003 values. In addition, the documentation of references in the spreadsheets was improved.

Planned Improvements

The default emission factor for N_2O from wastewater effluent has a high uncertainty. Future research may identify new studies that include updated data. The factor that accounts for non-sewage nitrogen in wastewater (bath, laundry, kitchen, industrial components) also has a high uncertainty. Several parameters constituting this factor are based on references that have since been updated, including Needs Survey (1996) and Metcalf & Eddy (1991). The uncertainty associated with this factor can likely be reduced incorporating more recent data.

Recalculations Discussion

Population estimates for the U.S. from 1990 through 2002 have been adjusted to include U.S. territories (i.e., American Samoa, Guam, Northern Mariana Islands, and the Virgin Islands). Emission estimates from previous years have only considered estimates of U.S. states and Puerto Rico. Overall, the change resulted in an average annual increase of 0.2 Tg CO_2 Eq. (1.7 percent) in N_2O emissions from wastewater treatment processes and effluent for the period 1990 through 2002.

8.4. Waste Sources of Ambient Air Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of ambient air pollutant emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2003 are provided in Table 8-14.

Table 8-14: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990		1997	1998	1999	2000	2001	2002	2003
NO_x	+		**3**	**3**	**3**	**2**	**2**	**2**	**2**
Landfills	+		2	2	3	2	2	2	2

Wastewater Treatment	+		+	+	+	+	+	+	+
Miscellaneous[a]	+		1	1	+	+	+	+	+
CO	**1**		**5**	**5**	**13**	**8**	**8**	**8**	**8**
Landfills	1		5	5	12	7	7	7	7
Wastewater Treatment	+		+	+	1	1	1	1	1
Miscellaneous[a]	+		+	+	+	+	+	+	+
NMVOCs	**673**		**157**	**161**	**140**	**119**	**122**	**133**	**125**
Landfills	58		32	33	27	23	23	25	24
Wastewater Treatment	57		62	63	59	51	53	58	54
Miscellaneous[a]	558		64	65	54	46	46	51	47

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.
Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 Gg

Methodology and Data Sources

These emission estimates were obtained from preliminary data (EPA 2004), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Emission estimates of these gases were provided by sector, using a "top down" estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty

No quantitative estimates of uncertainty were calculated for this source category. Uncertainties in these estimates, however, are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

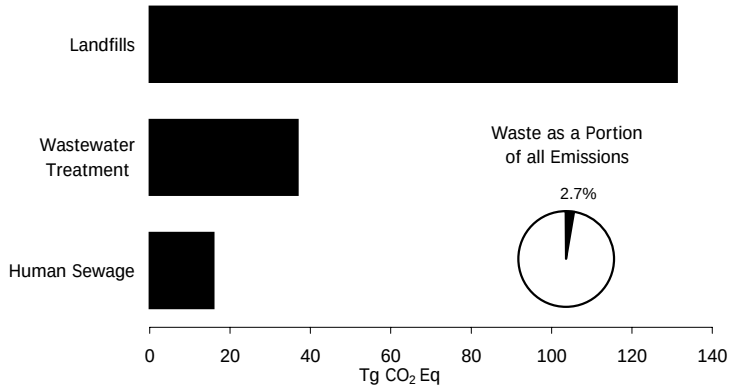

Figure 8-1: 2003 Waste Chapter Greenhouse Gas Sources